

LIFETIME AND g-FACTOR OF THE 181-keV LEVEL IN ^{78}Br

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Abstract: Low-lying states of ^{78}Br were populated by means of the nuclear reaction $^{78}\text{Se}(p, n)^{78}\text{Br}$. The observed γ -transitions were fitted into a level scheme. The half-life of the isomeric state at 181 keV was remeasured. Our result $T_{\frac{1}{2}} = 80 \pm 2 \mu\text{s}$ differs from the measurements of other groups. The g -factor of this state was determined to be $g = +1.02 \pm 0.02$ with the pulsed-beam DDCA method.

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NUCLEAR REACTIONS $^{78}\text{Se}(p, n\gamma)$, $E_p = 5.5, 10.0 \text{ MeV}$; measured $p\gamma(\theta, H, t)$.
 ^{78}Br deduced levels, $T_{\frac{1}{2}}$, g . Natural and enriched targets.

1. Introduction

An isomeric level in ^{78}Br was first reported by Duffield and Vegors¹⁾ in their investigations of the (γ, n) reactions on bromine. They observed a γ -transition of 149 keV with a half-life of $T_{\frac{1}{2}} = 127 \mu\text{s}$. Schardt and Goodman²⁾ remeasured the lifetime of this energy level ($T_{\frac{1}{2}} = 118 \mu\text{s}$) and determined its spin to be $J^\pi = 4^\mp$. According to the level scheme proposed by these authors, the isomeric state decays by a $\gamma\gamma$ cascade over a $2^\pm$ level at 32 keV to the 1^+ ground state. Recently Finckh *et al.*³⁾ investigated the level scheme of ^{78}Br with neutron time-of-flight measurements. They obtained a much more complete level scheme.

The aim of the present investigation is to measure the g -factor of the isomeric state in ^{78}Br by using the time-differential observation of the nuclear Larmor precession. With the determination of the g -factor, it is possible to confirm the spin and parity assignment and to decide on the configuration of this level. Since the magnetic moments of four states in the neighbouring doubly odd Br isotopes are available for comparison⁴⁾, the validity of the model used can be tested. Furthermore, the knowledge of the g -factor of this isomer is of interest for solid-state physics. Because of the relatively long lifetime, the natural line width is small, and therefore one is able to study the influence of internal fields acting on the excited nucleus with high precision.

2. Method

The g -factor of the 181 keV level of ^{78}Br was measured using the pulsed-beam DDCA method. This method is described extensively in ref. ⁵), and therefore only a short description will be given here.

An isomeric state with a mean-life τ is populated and simultaneously aligned to a certain extent by a nuclear reaction with a pulsed beam. If one applies an external homogeneous magnetic field H normal to the scattering plane, the angular distribution of the de-excitation γ -rays precesses around the magnetic field direction with the nuclear Larmor frequency

$$\omega_L = -gH\mu_N/\hbar. \quad (1)$$

Here, g is the nuclear g -factor, μ_N the nuclear magneton. Provided no internal perturbation fields are present, the γ -ray intensity observed at a time t and at an angle θ with respect to the beam axis (fig. 1) is given by ⁵):

$$I(t, H, \theta) = I_0 \exp(-t/\tau) \sum_{k \text{ even}} A_{kk} P_k(\cos(\theta - \omega_L t)). \quad (2)$$

The coefficients A_{kk} depend on the angular momenta involved in the transition and on the mechanism of the nuclear reaction; usually they are unknown. The P_k are the Legendre polynomials.

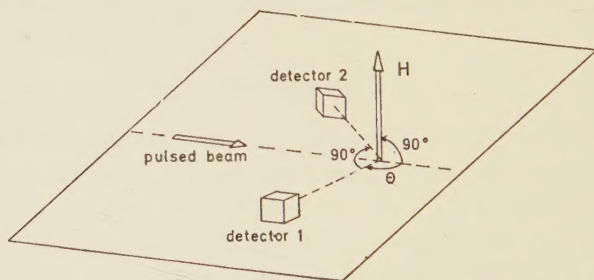


Fig. 1. Experimental set-up for the spin-rotation experiment.

Since the condition $A_{kk} \ll A_{22}$ for $k \geq 4$ is fulfilled in the present case, the frequency of the Larmor precession can be determined in a two-detector experiment from the ratio:

$$R(t, H, \theta) = \frac{I(t, H, \theta) - I(t, H, \theta + 90^\circ)}{I(t, H, \theta) + I(t, H, \theta + 90^\circ)} = \frac{3A_{22}}{4 + A_{22}} \cos 2(\theta - \omega_L t). \quad (3)$$

The phase angle of the cosine function in eq. (3) at $t = 0$ also yields the sign of the g -factor, provided the angle θ is chosen to be $\theta \neq \frac{1}{4}n\pi$, with $n = 0, 1, 2, \dots$. In case there are statistically fluctuating perturbation fields, eq. (3) has to be modified by an exponential attenuation factor $\exp(-t/\tau_{\text{rel}})$. Here τ_{rel} is the relaxation time of the nuclear alignment.

3. Experimental set-up and procedure

The measurements were performed with the proton beam of the Erlangen 12 MeV Tandem Accelerator. The beam ($E_p = 10.0$ MeV) was chopped into pulses of $2\mu\text{s}$ duration at a repetition time of $600\mu\text{s}$. The average current of the beam was several nA.

In the time differential measurements the γ -radiation was detected by 3.7 cm diam. $\times 1.2$ cm NaI(Tl) scintillators. Usually the detectors were placed at angles $\theta = \pm 135^\circ$. For the determination of the sign of the g -factor a measurement at angles $\theta_1 = 120^\circ$ and $\theta_2 = 210^\circ$ was carried out. The magnetic field was produced by a pair of Helmholtz coils.

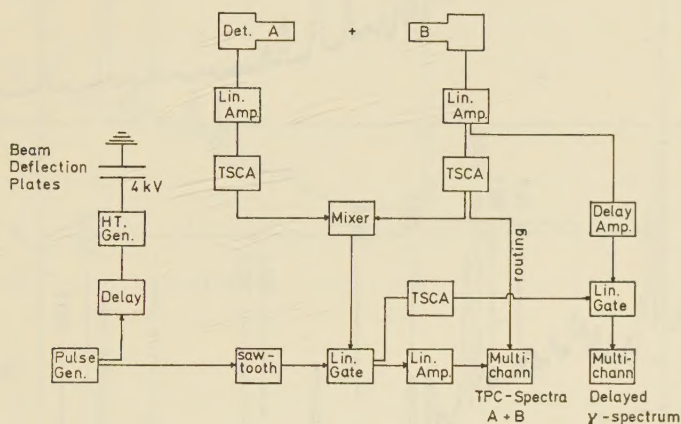


Fig. 2. Block diagram of the electronics.

A block diagram of the electronics used for the measurements of the half-life and the g -factor, is shown in fig. 2. The beam-pulsing system was triggered by a pulse generator which defined the pulse width and the repetition rate. Simultaneously it triggered a saw-tooth generator. The saw-tooth signal was gated by the energy-discriminated time signals. The two time spectra were stored in different sections of the multichannel memory.

Necessary for measuring magnetic moments with the DDCA method is the condition that the alignment of the excited nuclei must be preserved over a sufficiently long time interval, in this experiment over some tens of micro-seconds. It is known (see e.g. Bertschat *et al.*⁸⁾) that fast relaxation processes can be avoided, if targets of molten metals are used. Therefore the measurements of the g -factor were performed with a target of molten Se-Tl alloy (53 weight % selenium) which has the advantage of a low melting point of about 170°C . In order to reduce evaporation of selenium from the target, the complete target system (heating oven and target container) was placed in a glass tube filled with He gas of about 760 Torr. The proton beam entered the glass tube through a Havar foil of 1.8 mg/cm^2 thickness. The temperature of the target was measured and controlled by a thermo-couple.

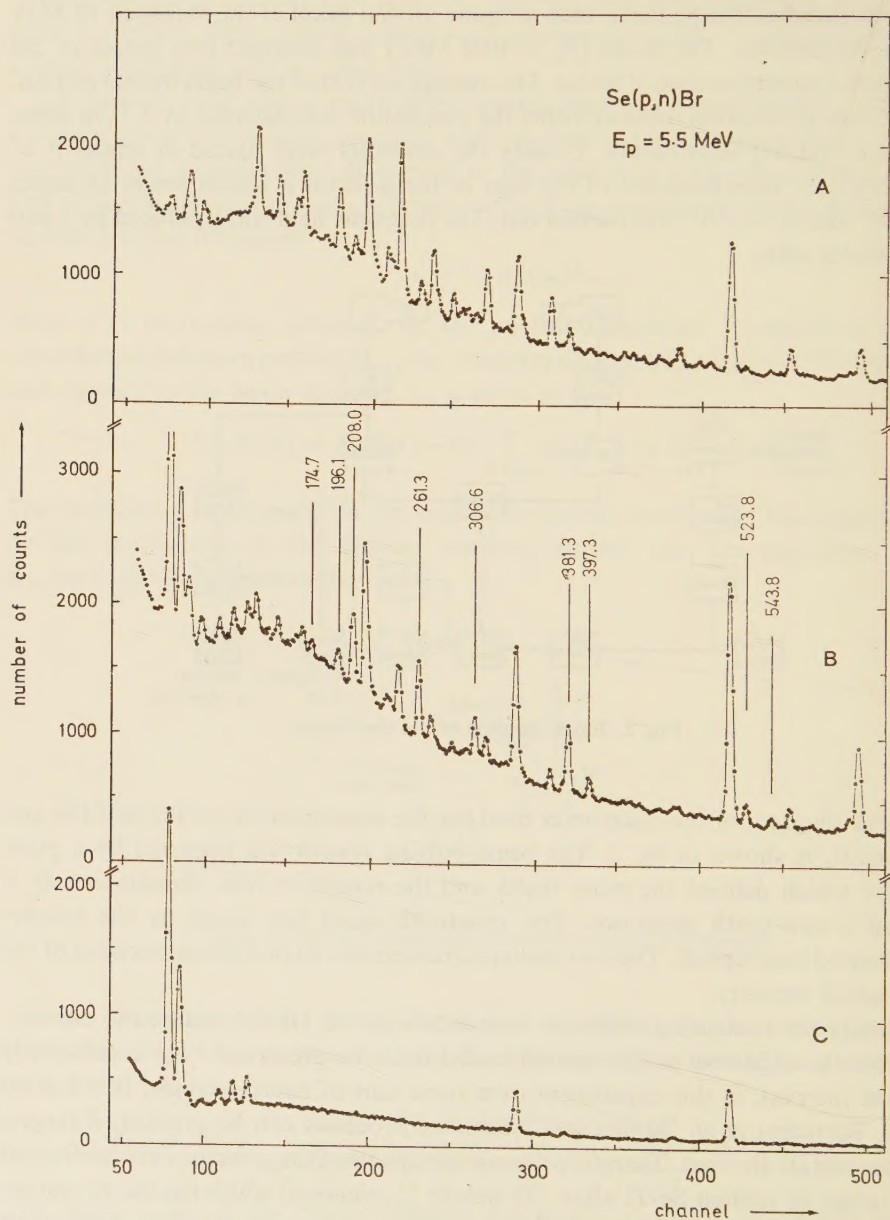


Fig. 3. Gamma-ray spectra following the reaction $\text{Se}(p,n)\text{Br}$ at $E_p = 5.5 \text{ MeV}$. A: Thick natural selenium target, B: Enriched (72.5%) ^{78}Se target melted onto a tungsten backing. C: γ -ray spectrum due to the tungsten backing. The spectra were taken with a $40 \text{ cm}^3 \text{ Ge}(\text{Li})$ -detector. Only the γ -rays corresponding to transitions in ^{78}Br are indicated. The energies are given in keV.

4. Results

4.1. THE γ -RAY SPECTRUM

The γ -ray spectra following the nuclear reaction $^{78}\text{Se}(p, n)^{78}\text{Br}$ at proton energies of 5.5 MeV and 10.0 MeV are shown in figs. 3 and 4. These spectra were obtained by a Ge(Li) detector (coaxially drifted, 40 cm³) and by a 3.7 cm diam. $\times$ 1.3 cm NaI(Tl)

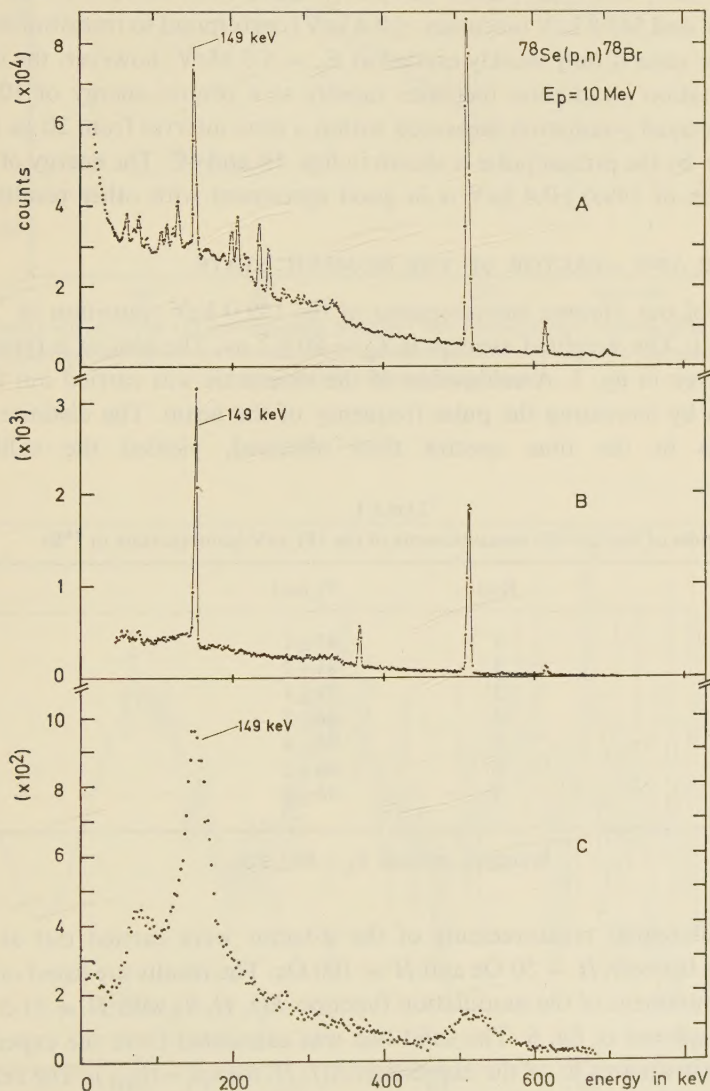


Fig. 4. Prompt and delayed γ -ray spectra from the reaction $^{78}\text{Se}(p, n)^{78}\text{Br}$ at $E_p = 10.0$ MeV. A: Prompt γ -ray spectrum of an enriched (72.5 %) ^{78}Se target measured with a Ge(Li) detector. B: Delayed γ -ray spectrum of an enriched (72.5 %) ^{78}Se target measured with a Ge(Li) detector. C: Delayed γ -ray spectrum of a natural selenium target measured with a NaI(Tl) scintillator. In figs. B and C the time interval after excitation by the proton pulse was chosen from 20 μs to 80 μs .

scintillator mounted on to a 56-DVP-photomultiplier. The energy scale was calibrated with the standard sources: ^{133}Ba , ^{22}Na , ^{137}Cs , and ^{60}Co . An enriched Se target † (72.5 % ^{78}Se) melted onto a tungsten backing was used.

The comparison between the spectrum taken at $E_p = 5.5$ MeV and a second one measured with a natural selenium target shows (fig. 3A and 3B) that the γ -rays of energies 174.7 keV, 196.1 keV, 208.0 keV, 261.3 keV, 306.6 keV, 381.3 keV, 397.3 keV, 523.8 keV and 543.8 keV (accuracy ± 0.4 keV) correspond to transitions in ^{78}Br .

The isomeric state is only weakly excited at $E_p = 5.5$ MeV; however, the intensity of the de-excitation γ -radiation increases rapidly at a proton energy of 10.0 MeV (fig. 4). The delayed γ -radiation measured within a time interval from 20 μs to 80 μs after excitation by the proton pulse is shown in figs. 4B and 4C. The energy of the isomeric transition of 149.0 ± 0.4 keV is in good agreement with other results $^{1, 2, 6}$).

4.2. HALF-LIFE AND g -FACTOR OF THE ISOMERIC STATE

The results of our lifetime measurements of the 149.0 keV transition in ^{78}Br are listed in table 1. The weighted average is $T_{\frac{1}{2}} = 80 \pm 2$ μs . The plot of a typical time spectrum is given in fig. 5. A calibration of the time scale was carried out for each individual run by increasing the pulse frequency of the beam. The distance of the prompt peaks in the time spectra thus obtained, yielded the calibration.

TABLE 1
Results of the half-life measurements of the 181 keV isomeric state in ^{78}Br

Run	$T_{\frac{1}{2}}$ (μs)
1	82 ± 1
2	84 ± 2
3	79 ± 1
4	86 ± 2
5	69 ± 4
6	80 ± 2
7	74 ± 2

Weighted average $T_{\frac{1}{2}} = 80 \pm 2$ μs

The time-differential measurements of the g -factor were carried out at several magnetic fields between $H = 50$ Oe and $H = 100$ Oe. The results are listed in table 2. A typical measurement of the modulation function $R(t, H, \theta)$ with $H = 51.5$ Oe and $\theta = 135^\circ$ is displayed in fig. 6. The solid line was calculated from the experimental points by a least-squares fit of the expression $R(t, H, \theta)\exp(-t/\tau_{\text{rel}})$. The relaxation time in fig. 6, which corresponds to a temperature of about 390°C of the Se-Tl target is $\tau_{\text{rel}} = 40 \pm 30$ μs . The sign of the g -factor was extracted from a two-detector-

† We want to express our thanks to Dr. E. Finckh of the Hahn-Meitner-Institut, Berlin, for supplying us with the enriched ^{78}Se target.

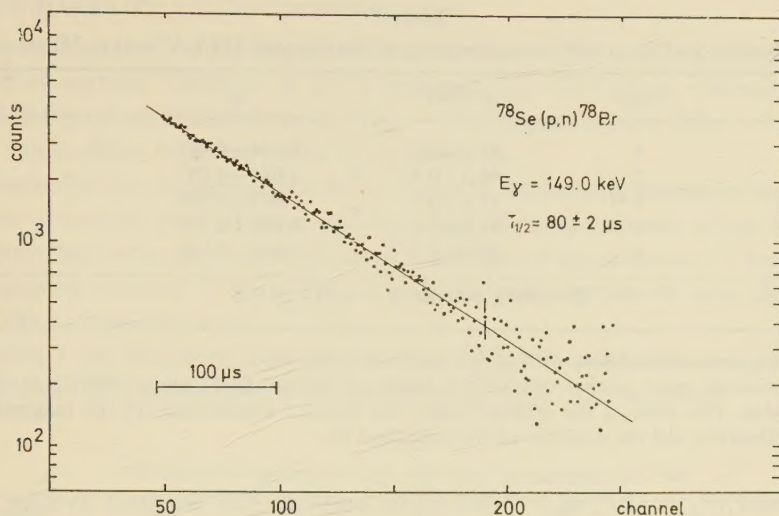


Fig. 5. Decay curve of the 181 keV isomeric state in ^{78}Br . The solid line corresponds to a least-squares fit to the experimental points. A constant background of 6000 counts, also obtained from the least-squares fit, is already subtracted.

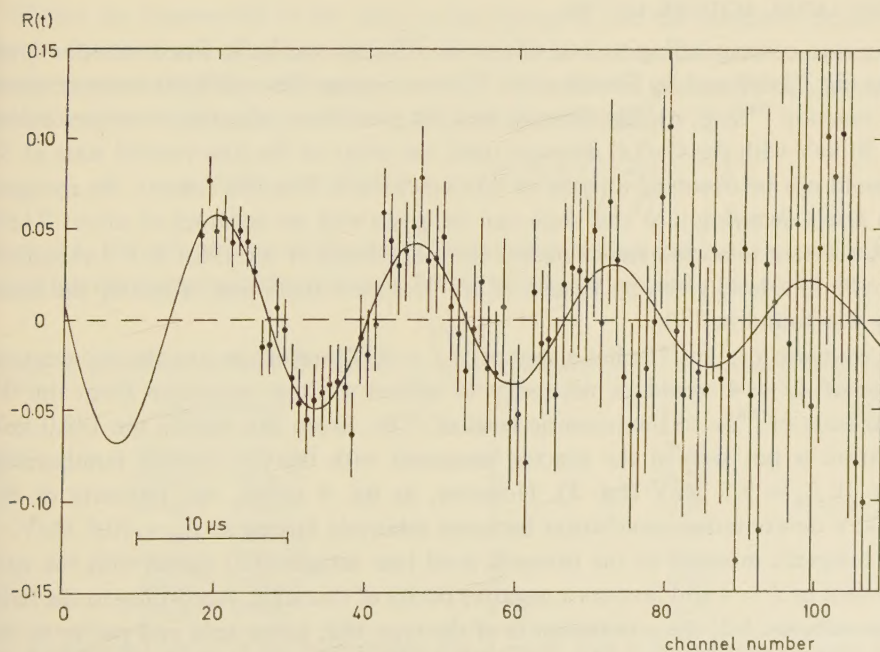


Fig. 6. Modulation of the γ -ray intensity caused by the spin precession of the excited ^{78}Br nuclei in an external magnetic field of $H = 51.5$ Oe, measured in molten Se-Tl alloy (temperature 390°C) at an angle $\theta = 135^\circ$. The solid line corresponds to a least-squares fit.

TABLE 2

Summary of the g -factor measurements of the isomeric 181 keV level in ^{78}Br

Run	H (Oe)	g
1	96.3 ± 0.9	0.984 ± 0.087
2	96.3 ± 0.9	1.049 ± 0.053
3 ^{a)}	51.5 ± 0.5	1.003 ± 0.030
4	51.5 ± 0.5	0.993 ± 0.078
5	63.8 ± 0.1	1.072 ± 0.100

Weighted average: $g = 1.017 \pm 0.020$ ^{a)} The spin precession pattern of this run is shown in fig. 6.

The experiments were carried out with a target of molten Se-Tl alloy (390°C) at different magnetic fields. The error of the g -factor takes into account uncertainties of the magnetic field, the time calibration and the accuracy of the numerical fit.

measurement ($\theta_1 = 120^\circ$, $\theta_2 = 210^\circ$) to be positive. The weighted average of all measurements yields $g = +1.02 \pm 0.02$. This value is not corrected for diamagnetic shielding and the Knight shift, since these effects are small compared with the experimental error.

5. Discussion

5.1. THE LEVEL SCHEME OF ^{78}Br

All γ -rays corresponding to transitions in ^{78}Br can easily be fitted into the level scheme (fig. 7) deduced by Finckh *et al.* ³⁾ from neutron time-of-flight measurements of the reaction $^{78}\text{Se}(p, n)^{78}\text{Br}$. Since it was not possible to observe γ -energies below $E_\gamma \approx 50$ keV with the Ge(Li) detector used, the delay of the first excited state at 32 keV could not be observed directly in our experiment. For this reason, the energies of the levels decaying into this state can be given with an accuracy of about 2 keV only. Uncertain to some extent remains the assignment of the 196.1 keV γ -radiation to the 195 keV level given by Finckh *et al.* ³⁾, since a transition of nearly the same energy was found in ^{80}Br .

The isomeric level in ^{78}Br has a spin of 2^+ $J = 4$. Therefore an angular momentum transfer of $\Delta J = 4$ would be necessary to induce a direct transition from the 0^+ ground state of ^{78}Se to the isomeric level of ^{78}Br . From this reason the 149.0 keV γ -radiation is not seen in the spectra measured with the low proton bombarding energy of $E_p = 5.5$ MeV (fig. 3). However, as fig. 4 shows, the intensity of the 149.0 keV de-excitation γ -radiation becomes relatively strong at $E_p = 10.0$ MeV.

The magnetic moment of the isomeric level (see subsect. 5.3) agrees with the spin assignment of $J = 4$ and favours a negative parity of this state. According to the half-life (see subsect. 5.2) the γ -radiation is of the type M2; hence spin and parity of the first excited level of ^{78}Br would be $J^\pi = 2^+$. If this assignment is correct, the 2^+ level should decay with a half-life of some tens of nanoseconds. A measurement of this lifetime could clarify these questions.

5.2. THE HALF-LIFE OF THE ISOMERIC LEVEL

A measurement of the lifetime of the isomeric level in ^{78}Br has already been reported by several authors. Duffield *et al.*¹⁾ obtained $T_{\frac{1}{2}} = 127 \pm 5 \mu\text{s}$, Scharadt *et al.*²⁾ $T_{\frac{1}{2}} = 118.0 \pm 1.5 \mu\text{s}$, McCarthy *et al.*⁶⁾ $T_{\frac{1}{2}} = 126.5 \mu\text{s}$ and Ivanov⁷⁾ $T_{\frac{1}{2}} = 121 \pm 12 \mu\text{s}$. These values differ from our value $T_{\frac{1}{2}} = 80 \pm 2 \mu\text{s}$.

A reason for this discrepancy could be due to an incorrectly estimated background. In order to exclude any failure of our experimental equipment and of our evaluation procedure, we remeasured the well-known half-life of the isomeric 1^+ level in ^{88}Y . The obtained value of ⁹⁾ $T_{\frac{1}{2}} = 295 \pm 5 \mu\text{s}$ is in good agreement with the value of $T_{\frac{1}{2}} = 300 \mu\text{s}$ reported in refs.¹⁰⁻¹⁴⁾.

In table 3 the Weisskopf estimates for the 149.0 keV γ -radiation are given. From this follows that the isomeric level should decay by a M2 transition.

TABLE 3
Weisskopf estimates for the 149.0 keV γ -transition in ^{78}Br

Type of transition	E1	M1	E2	M2	E3	M3
$T_{\frac{1}{2}} (\mu\text{s})$	$1 \cdot 10^{-7}$	$6 \cdot 10^{-7}$	$3 \cdot 10^{-1}$	6	$2 \cdot 10^6$	$1 \cdot 10^7$

5.3. THE g -FACTOR OF THE 181 keV LEVEL IN ^{78}Br

Within the framework of the shell model, the spins and the magnetic moments of the ground state and of the low-lying excited states in doubly odd nuclei are determined by the properties of the odd-proton and the odd-neutron groups. In this model, the g -factor of a doubly odd nucleus is given by the expression¹⁵⁾

$$g = \frac{1}{2}(g_{\pi} + g_{\nu}) + \frac{1}{2}(g_{\pi} - g_{\nu}) \frac{J_{\pi}(J_{\pi} + 1) - J_{\nu}(J_{\nu} + 1)}{J(J + 1)}. \quad (4)$$

In eq. (4) the subscripts π and ν stand for the odd proton and neutron, respectively. Inserting the single-particle values (Schmidt values) for g_{π} and g_{ν} in eq. (4) one often

TABLE 4
Values of g -factors calculated for various possible configurations of the isomeric level in ^{78}Br

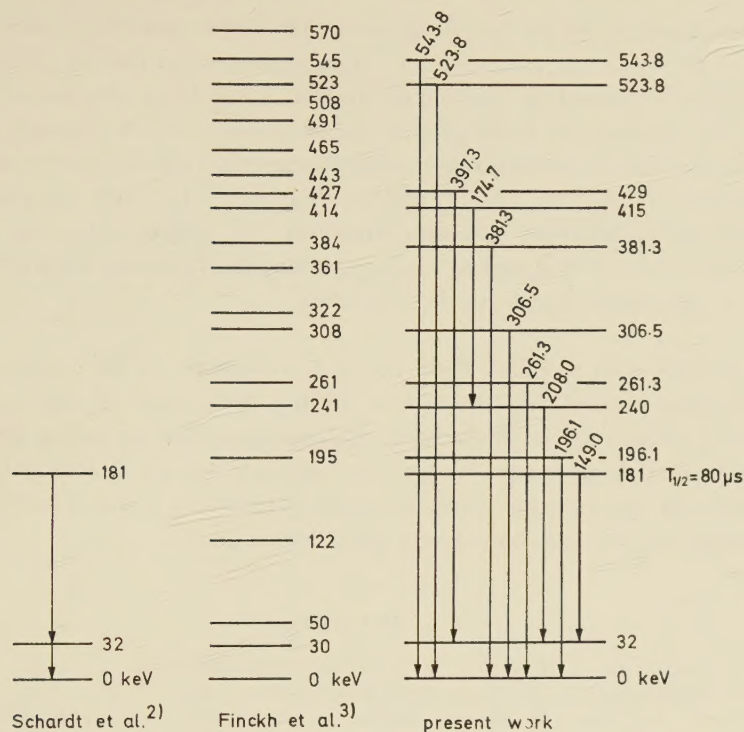
	Configuration	J^{π}	g_{calc}	g_{exp}
(a)	$(\pi 2p_{\frac{3}{2}})^{-1} (\nu 1g_{\frac{7}{2}})^{\frac{3}{2}}$	4^{-}	+0.05	$+1.02 \pm 0.02$
(b)	$(\pi 2p_{\frac{3}{2}})^{-1} (\nu 1g_{\frac{9}{2}})^{\frac{3}{2}}$	4^{-}	-0.26	
(c)	$(\pi 1g_{\frac{7}{2}})^1 (\nu 2p_{\frac{3}{2}})^1$	4^{-}	+1.25	
(d)	$(\pi 1g_{\frac{7}{2}})^1 (\nu 1g_{\frac{7}{2}})^{\frac{3}{2}}$	4^{+}	+0.82	
(e)	$(\pi 1g_{\frac{9}{2}})^1 (\nu 1g_{\frac{7}{2}})^{\frac{3}{2}}$	4^{+}	+0.51	
(f)	$(\pi 1f_{\frac{7}{2}})^3 (\nu 1g_{\frac{7}{2}})^{\frac{3}{2}}$	4^{-}	-0.05	
(g)	$(\pi 1f_{\frac{7}{2}})^3 (\nu 1g_{\frac{9}{2}})^{\frac{3}{2}}$	4^{-}	-0.14	

The experimental values of the neighbouring odd- A nuclei used in the calculations were: proton states: $g = +1.41$ for $p_{\frac{3}{2}}$ state (^{79}Br), $g = +1.23$ for $g_{\frac{7}{2}}$ state (^{77}As) and $g = +0.46$ for $f_{\frac{5}{2}}$ state (^{75}As , ^{83}Rb). neutron states: $g = +1.07$ for $p_{\frac{3}{2}}$ state (^{77}Se), $g = -0.29$ for $(g_{\frac{7}{2}})^{\frac{3}{2}}$ state and $g = -0.22$ for $g_{\frac{9}{2}}$ state (^{83}Kr). The experimental values are taken from ref. 4).

TABLE 5
Comparison of experimental and calculated g -factors of doubly odd nuclei between $A = 72$ and $A = 86$

Nucleus	Configuration	J^π	g_{calc}	g_{exp}	Remarks
^{72}Ga	$(\pi 2p_{3/2})^{-1} (\nu 1g_{9/2})_{1/2}^3$	3^-	-0.29	-0.044 ref. ²⁰⁾	$g_\pi = +1.52$ (^{69}Ga , ^{71}Ga) $g_\nu = -0.29$ (^{79}Se)
^{76}As	$(\pi 1f_{7/2})^1 (\nu 1g_{9/2})_{1/2}^3$	2^-	-0.35	-0.453 ref. ²¹⁾	$g_\pi = +0.35$ (^{75}As) $g_\nu = -0.29$ (^{79}Se)
^{76}Br	$(\pi 1g_{7/2})^1 (\nu 1g_{9/2})_{1/2}^1$	$1(+)^+$	$+0.52$	0.548 ref. ¹⁷⁾	$g_\pi = +1.23$ (^{77}As) $g_\nu = -0.20$ (^{73}Ge)
^{78}Br	$(\pi 1g_{7/2})^1 (\nu 2p_{3/2})_{1/2}^1$	4^-	$+1.25$	$+1.02$ present work	$g_\pi = +1.23$ (^{77}As) $g_\nu = +1.07$ (^{77}Se)
^{80}Br	$(\pi 1g_{7/2})^1 (\nu 1g_{9/2})_{1/2}^5$	1^+	$+0.51$	0.514 ref. ¹⁸⁾	$g_\pi = +1.23$ (^{77}As) $g_\nu = -0.22$ (^{83}Kr)
^{80}Br	$(\pi 2p_{3/2})^{-1} (\nu 1g_{9/2})_{1/2}^5$	5^-	$+0.24$	$+0.263$ ref. ¹⁸⁾	$g_\pi = +1.46$ (^{79}Br , ^{81}Br) $g_\nu = -0.29$ (^{79}Se)
^{82}Br	$(\pi 2p_{3/2})^{-1} (\nu 1g_{9/2})_{1/2}^{-3}$	5^-	$+0.25$	$+(-)0.325$ ref. ²²⁾	$g_\pi = +1.51$ (^{81}Br) $g_\nu = -0.29$ (^{79}Se)
^{82}Rb	$(\pi 2p_{3/2})^{-1} (\nu 1g_{9/2})_{1/2}^5$	5^-	$+0.21$	$+0.302$ ref. ²³⁾	$g_\pi = +1.37$ (^{81}Rb) $g_\nu = -0.29$ (^{79}Se)
^{84}Rb	$(\pi 1f_{7/2})^{-1} (\nu 1g_{9/2})_{1/2}^{-3}$	2^-	-0.88	-0.660 ref. ²³⁾	$g_\pi = +0.55$ (^{83}Rb , ^{85}Rb) $g_\nu = -0.22$ (^{83}Kr)
^{86}Rb	$(\pi 1f_{7/2})^{-1} (\nu 1g_{9/2})_{1/2}^{-1}$	2^-	-0.89	-0.845 ref. ¹⁹⁾	$g_\pi = +0.54$ (^{85}Rb) $g_\nu = -0.23$ (^{85}Kr , ^{87}Sr)

The experimental g -factors of the odd-proton and the odd-neutron groups, inserted into eq. (4) are given in the last column of the table. The values are taken from the table of nuclear moments in ref. ⁴⁾.

Fig. 7. Level scheme of ^{78}Br .

obtains sufficiently good agreement between theory and experiment, although the single-particle model ignores contributions due to the interaction with the residual nucleus. These are taken into account to a first approximation, if one uses, rather than the single-particle values, the experimental g -factors of the corresponding states of the adjacent odd-proton and odd-neutron nuclei exhibiting the proper spins and parities. The lowest states of the two neighbouring odd- N nuclei ^{77}Se and ^{79}Kr have spin and parity $J^\pi = \frac{1}{2}^-$ and $\frac{7}{2}^+$, respectively; in the odd- Z nuclei ^{77}Br and ^{79}Br , the $\frac{3}{2}^-$ and $\frac{9}{2}^+$ states correspond to the ground state and to the first excited state, respectively. The low-lying levels of ^{78}Br should result from combinations of these configurations. In table 4, the g -factors calculated according to eq. (4) are shown; furthermore, the configuration $(\pi 1f_{7/2})^3$ is taken into account. Since the agreement between the experimental and the half-empirical g -factors calculated in this manner is usually good in this mass region (see table 5), only the configurations (c) and (d) of table 4 may be drawn into consideration for the isomeric state in ^{78}Br . The present experiment does not allow a distinction between the two possibilities. However, the coupling rules of Brennan and Bernstein¹⁶⁾ contain a helpful hint; according to their rules, the lowest state of the configuration $(\pi 1g_{7/2})^1 (v 2p_{3/2})^1$ is 4^- , while the lowest state for the configuration $(\pi 1g_{7/2})^1 (v 1g_{7/2})^3$ is expected to be 8^+ . Thus, the most probable configuration, although not the only one possible, for the second excited state in ^{78}Br is $[(\pi 1g_{7/2})^1 (v 2p_{3/2})^1]_{4^-}$.

Table 5 contains all the known g -factors of doubly odd nuclei between $A = 72$ and $A = 86$. With the exception of ^{72}Ga , all the experimental g -factors can be satisfactorily explained by this simple model. Aside from this model, there exists only a few attempts to make predictions or explanations of magnetic moments in doubly odd nuclei of this mass region with other models (e.g. inclusion of deformation in ^{76}Br , ref. ¹⁷), in ^{80}Br , ref. ¹⁸) and in ^{86}Rb , ref. ¹⁹)). These are able to explain the measured quadrupole moments. However, no progress over the simple shell model can be observed regarding magnetic moments. Therefore no attempt has been made to apply these models to the ^{78}Br case.

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